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Computational Architecture for Integrated Controls and Structures Design

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Abstract

To facilitate the development of Control-Structure Interaction (CSI) design methodology, this paper presents a computational architecture for interdisciplinary design of active structures. The emphasis of the computational procedure is to exploit existing sparse matrix structural analysis techniques, in-core data transfer with control synthesis programs, and versatility in the optimization methodology to avoid unnecessary structural or control calculations. The architecture is designed such that all required structure, control and optimization analyses are performed within one program. Hence, the optimization strategy is not unduly constrained by "cold" starts of existing structural analysis and control synthesis packages.

Design of Closed-Loop Spacecraft Dynamics

Conventional attitude and station keeping control system design, which maintain bandwidth separation between rigid-body controllers and flexible-body dynamics, cannot meet the performance goals of future science missions. Thus, both the rigid and flexible-body closed-loop dynamics of the spacecraft must be concurrently designed. The interdisciplinary design of controller and structure dynamics can be studied most easily through computer simulation. To this end, a computational software testbed has been designed and implemented to test new ideas and algorithms for future spacecraft design.

The software testbed consists of three in-core modules: a structural modeling and analysis module, a control synthesis processor, and a versatile optimization package. Key features of the software include in-core data transfer between the control, structure, and optimization modules and a sparse matrix utility. Both features facilitate new implementations of solution algorithms and control strategies.

The software testbed has been applied as a research tool to study CSI partitioned analysis procedures[1], suboptimal second order observers[2], and a number of truss design problems. The discussion herein emphasizes use of the software architecture to reduce the computational burden of CSI analysis, synthesis, and/or simulation. By reducing burdensome data transfer among separate analysis packages and by increasing the computational efficiency, more freedom is allowed to explore closed-loop spacecraft dynamics design methodology. A description of the architecture and its implementation in a prototype code are discussed. Examples of active truss designs are also presented.

COMPUTATIONAL ARCHITECTURE FOR INTEGRATED CONTROLS AND STRUCTURES DESIGN

OBJECTIVE:

Develop a computational architecture for the study of CSI that reduces data handling and thus promotes more study of design methodology.

APPROACH:

Assemble public domain software into a single program for in-core data transfer between structures, controls and optimization analysis software.

Benefits of Interdisciplinary Design

Several tangible benefits usually result from an integrated design approach for controlled structures. These include minimizing structural mass, decreasing the amount of controller energy, and increasing system robustness.[3-7] These benefits are usually the first and sometimes the only benefits considered from the integrated design approach. There exist, however, intangible benefits that must not be overlooked. The interaction of engineers and scientists from controls and structures disciplines produces new insight into active structure design. Specifically, the implications that changes in one discipline have on another discipline are better understood. This leads to physical insight into CSI and permits the portion of the design relegated to the computer to be minimized.

Developing physical insight into the interrelationship of the structure and control system will enable substantial improvements in spacecraft design. Most importantly, increased physical insight will aid the systems level decision process which ultimately determines the viability of a mission from both cost and technical considerations. Physical insight into interdisciplinary CSI design has motivated the present computational approach.

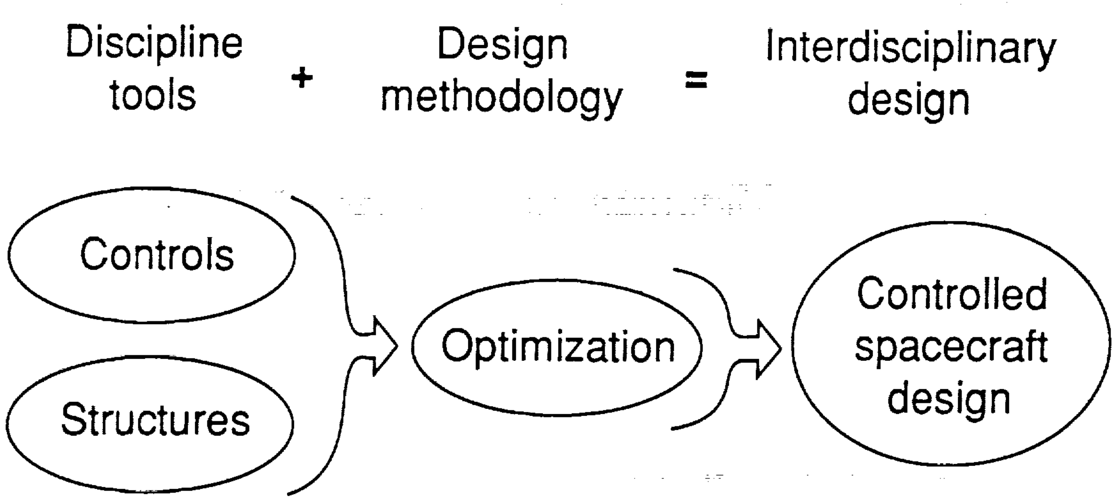
- TANGIBLE
  - Minimization of mass
  - Reduced controller energy
  - Enhanced robustness

- INTANGIBLE
  - Physical insight into CSI
  - Better informed decisions

Optimization - A Tool for Studying Design Methodology

Significant advances in the use of optimization as a design tool for interdisciplinary problems were presented at a recent Symposium on Multidisciplinary Analysis and Optimization.[8] Methods for determining objective function and constraint sensitivities for both control and structure design variables are becoming more analytic in nature. Data base systems for managing shared structure and control data are being used to link analysis software.[9,10] Unfortunately, formulating the correct objectives and constraints for interdisciplinary problems still remains a subject of research.

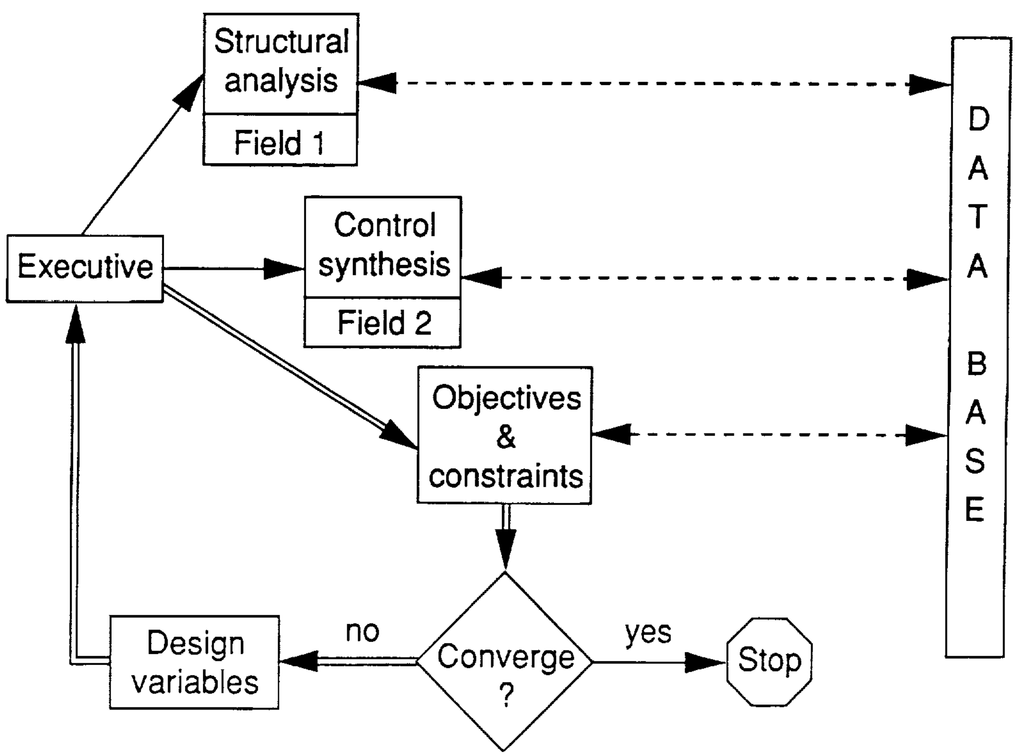
Optimization can be used as a tool for studying the effects of different objectives and constraints. From experience the designer gains insight into appropriate formulations of the problem. Sensitivity calculations, which are an integral part of optimization analysis, yield physical insight. Hence, optimization can be a tool for studying design methodology. It is in this context that optimization will play a key role in CSI technology development.



Conventional Architecture for Coupled-Field Problems

To date, most designs which consider both the controller and structure as design variables have been performed using an ad hoc collection of discipline specific software modules. Such software tools were originally developed for the solution of single-field problems (e.g. control law synthesis, finite element structural modeling). The use of these tools has required specialized interfaces to be developed which must transfer data from one module to the next as shown below.

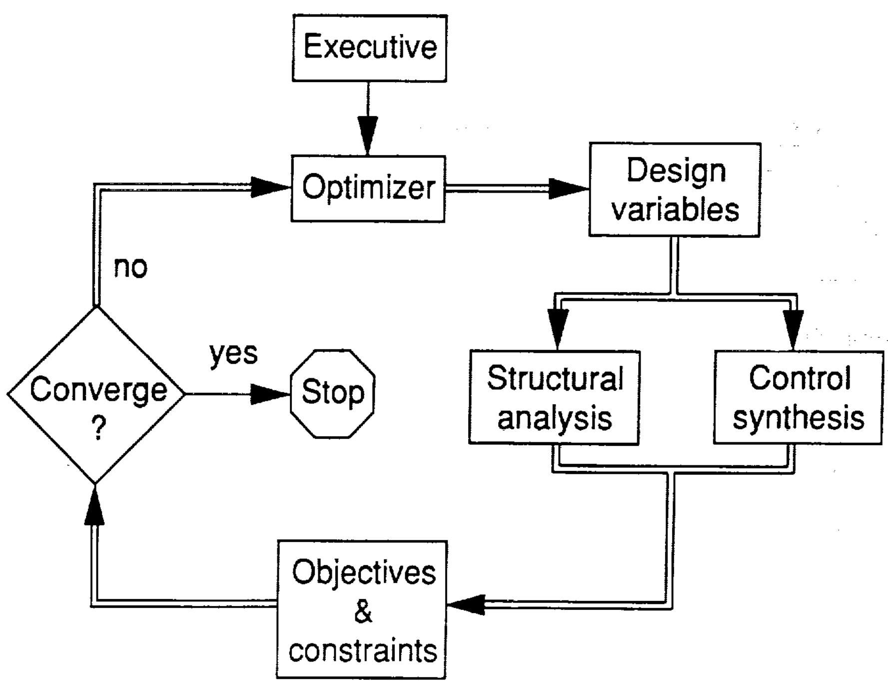
Integration of such single-field analysis codes by means of a common data base manager yields an executive-type program. It provides for immediate usage of existing software. However, the executive program is usually hardwired to a few design methods thereby losing versatility. Moreover, the high cost associated with 'cold' starts of structural analysis or control synthesis packages discourages asking "What if?" The use of loosely coupled single-field programs also masks the physics associated with CSI. Hence, the need for a new architecture for the coupled-field optimization problem is indicated.



Proposed Architecture for Coupled-Field Problems

To alleviate some of the computational problems associated with integrated design of structures and controllers, an in-core architecture is proposed as shown below. The objectives of the procedure are to exploit sparse matrix structural analysis procedures, in-core data transfer with control synthesis algorithms, and to maintain versatility in the optimization methodology. The architecture is designed so that all required structure, control and optimization analyses are performed within one executable program.

Although the available memory (virtual memory) of new computers has grown dramatically in recent years, some very large problems must still be solved out-of-core. Data-base type design codes will continue to be needed to handle very large problems for the foreseeable future. The proposed architecture is targeted for research studies of design methodology for small to moderate size problems (1000 structural degrees of freedom). The benefits of this approach are described next.



Benefits of the Proposed Integrated Design Architecture

Several advantages exist in using the proposed architecture versus the conventional data base approach. First, the computational speed can be improved using in-core data transfer (i.e. common blocks instead of data bases). Coupling the Input/Output time savings with algorithms that exploit matrix sparsity and the second order form of structures equations enables moderate size problems to be solved routinely. Second, the new architecture requires engineers and scientists from both controls and structures disciplines to work more closely. Since they both use the same software tool, a conducive software environment exists for exploring interdisciplinary problems. Finally, the in-core architecture permits much more flexibility in asking 'What if?' questions.

If optimization will be used as the tool for studying the physics of CSI, it becomes imperative to provide as much freedom as possible to study different design methodologies. In particular, there should be a great deal of freedom in selecting objective functions and constraints. By connecting the essential software in one executable program, the proposed architecture reduces the computational burden which permits the researcher more time to study methodology and problem formulation.

- Increased speed
  - Sparse matrix procedures
  - Fewer repeat calculations
- Encourages interdisciplinary design
- Freedom to ask, "What if?"

Prototype Code - Controlled Structure Simulation Software (CS^3)

A prototype code called CS^3 has been developed using public domain software to implement the proposed architecture. The key feature sought in choosing the software is the availability of source code which could be modified to permit in-core data transfer among the different programs. There exist many other possible choices for the optimizer, structural analysis and control synthesis than the ones presented herein.

The executive program is simply one that tests input data to determine whether analysis or optimization is to be performed. If optimization is to be performed, the program flow is governed by the optimizer.

The optimization path uses the Automated Design Synthesis (ADS)[11] system of subroutines written by Dr. Gary Vanderplatts. A number of solution strategies may be chosen within the ADS system. Currently objective and constraint sensitivities are performed by finite differences; however, analytic and semi-analytic sensitivity modules will be added to CS^3.

Structural finite element modeling, real-symmetric eigenvalue analysis, and transient response calculations are performed with a code called Linear Analysis of Sparse Structures (LASS). LASS has been written and/or collected by the NASA Langley Research Center and the University of Colorado.

Control synthesis is performed using the Optimal Regulator Algorithms for the Control of Linear Systems (ORACLS)[12] library of linear algebra subroutines. ORACLS is a system for Linear-Quadratic-Gaussian control law design developed by Dr. E. S. Armstrong.

PROTOTYPE CODE - CS^3

CONTROLLED STRUCTURE SIMULATION SOFTWARE

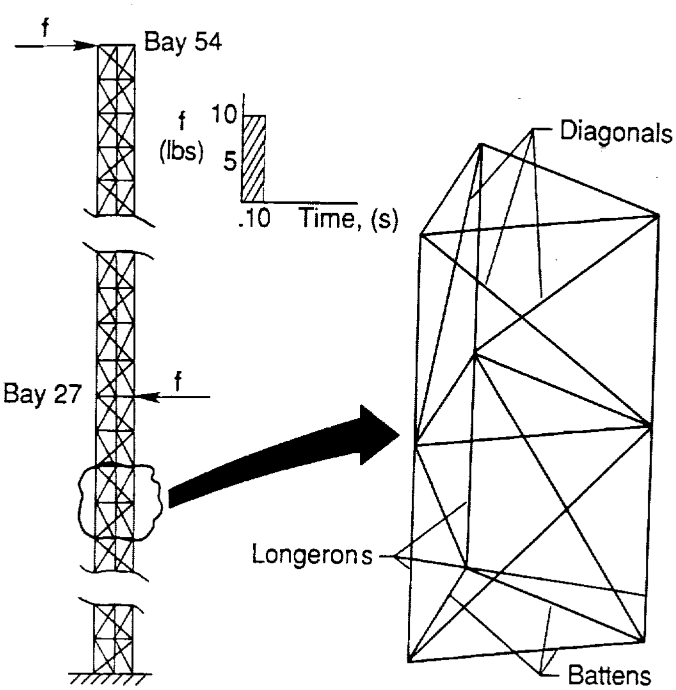
- Executive - User supplied
- Optimization - ADS (Vanderplatts)
- Structures - LASS (NASA LaRC, University of Colorado)
- Controls - ORACLS (NASA LaRC)

Truss-Beam Design Example

The truss-beam shown below has been used to demonstrate the use of CS^3. The three-longeron, single-laced truss was modeled by finite elements with one beam element from joint-to-joint. The model had 165 nodes and 990 degrees of freedom. More detailed information is presented in reference 13. Three design variables were chosen: the outside diameters of the batten, diagonal and longeron. All members were tubular with the inside diameter equal to 75 percent of the outer diameter.

The objective was to minimize a quadratic cost function by tailoring the structure. Seven modes were used in the control law design. Weighting matrices in the cost function which influence the control law were implicit functions of the design variables. Constraints consisted of forcing the total mass of the structure not to exceed the nominal design mass, and a restriction on local beam vibration frequencies.

Truss-beam

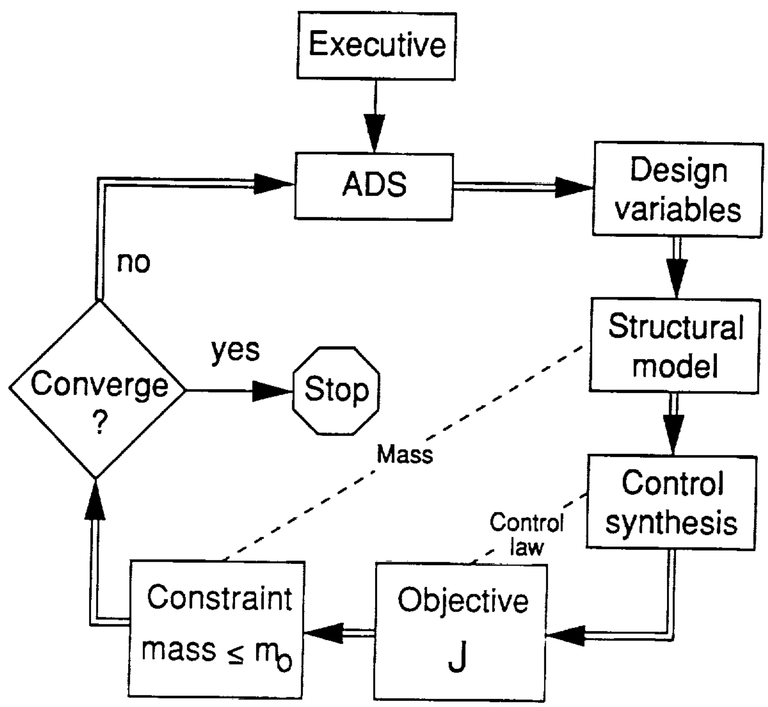


Quadratic cost function

$$J = \int_{t_0}^{t_1} \frac{1}{2}\left(x^T Q x + u^T R u\right) d\tau$$

CS^3 Flowchart For Truss-Beam Design

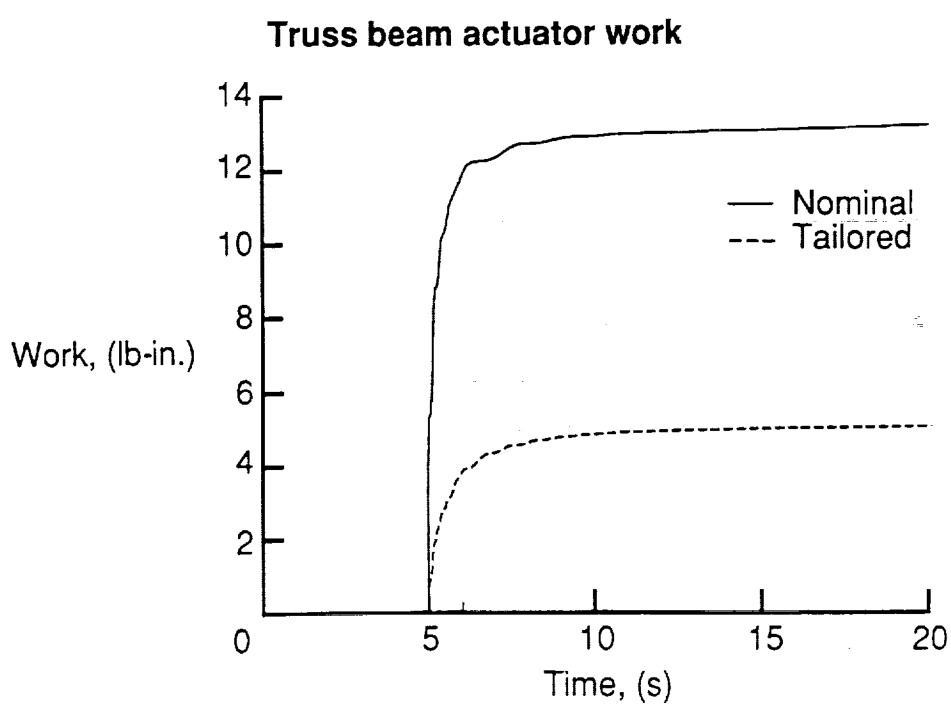
The flowchart below shows the steps used to tailor the truss-beam to minimize the quadratic cost function. All data were transferred in-core (virtual memory) on a SUN 3 workstation. Problem dependent objective and constraint evaluation subroutines enable virtually unlimited freedom in formulating the problem. Data transfer among subroutines through common blocks permits intermediate results computed in one calculation to be used in another computation, even when the second computation occurs in a different subroutine. This greatly enhances the computational speed of the design process.



Truss-Beam Optimized Design

The table below lists the nominal and optimized tube diameters. The optimal design was obtained in 18 iterations with each iteration taking about 10 minutes. Note that considerable time savings are possible if analytic derivatives rather than finite differences were used to compute sensitivities. The figure below shows the actuator work for the nominal and optimized beam subjected to the same performance requirement of reducing the tip vibration amplitude below 0.025 in. within 10 seconds. The optimized beam requires 56 percent less actuator work.

Outside tube diameter, in.	Nominal	Tailored
Longeron	0.789	1.717
Diagonal	1.707	1.284
Batten	0.918	0.640



Physical Insight Into Truss-Beam Design

The results of the truss-beam optimization have been noted to involve maximizing a quantity related to the stiffness of the structure[13]. The truss-beam optimization used the following weighting matrices:

$$\mathbf{Q} = \begin{bmatrix} \mathbf{K} & 0 \\ 0 & \mathbf{M} \end{bmatrix} \qquad \mathbf{R} = \begin{bmatrix} \mathbf{D}^T\mathbf{K}^{-1}\mathbf{D} \end{bmatrix}$$

where, $\mathbf{K}$ is the stiffness matrix, $\mathbf{M}$ is the mass matrix and $\mathbf{D}$ is the actuator location matrix.

To minimize this quadratic measure of the energy, subject to a constraint on total mass, it is found that the optimal solution is one that maximizes a measure of the structural stiffness. Thus, the question arises, what is the proper way to pose the integrated structure and control design problem to give a balanced solution between structures and controls? That is, a solution is desired which does not imply making the structure as stiff as possible within a mass budget. This remains an open question for research, and will be addressed through the next example problem.

Minimize $\longrightarrow$ $\frac{1}{2}\,(x^TQx + u^TRu)$

$\Downarrow$

Implies

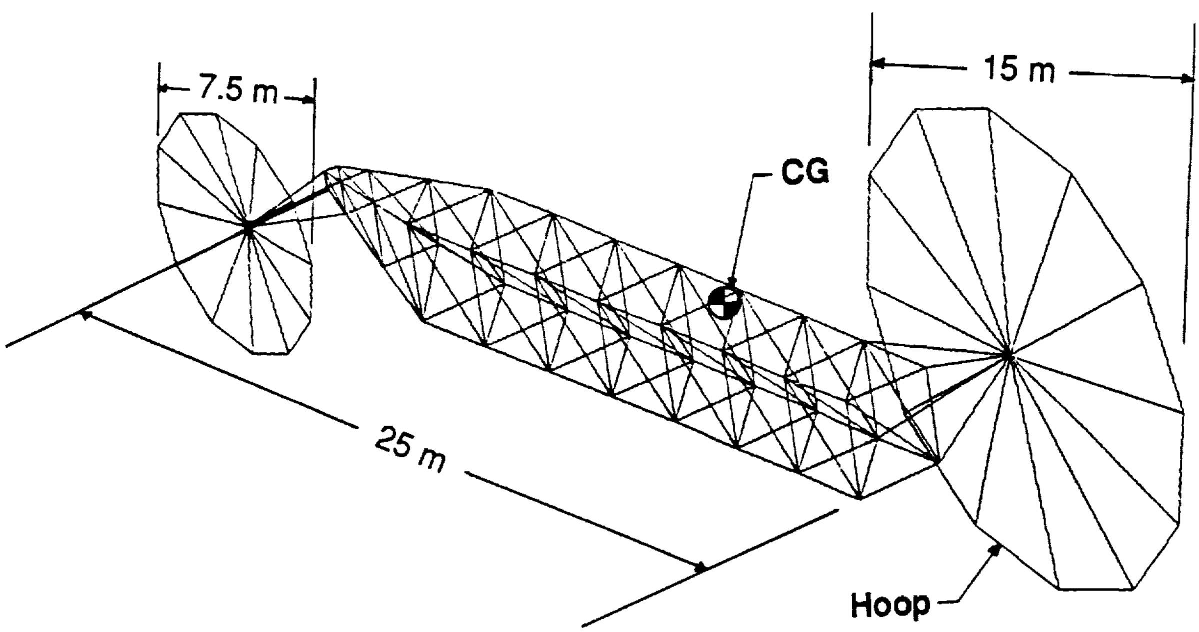
Maximize $\longrightarrow$ Stiffness

What objective requires balanced levels
of stiffness and control?

Earth Pointing Satellite Design Problem

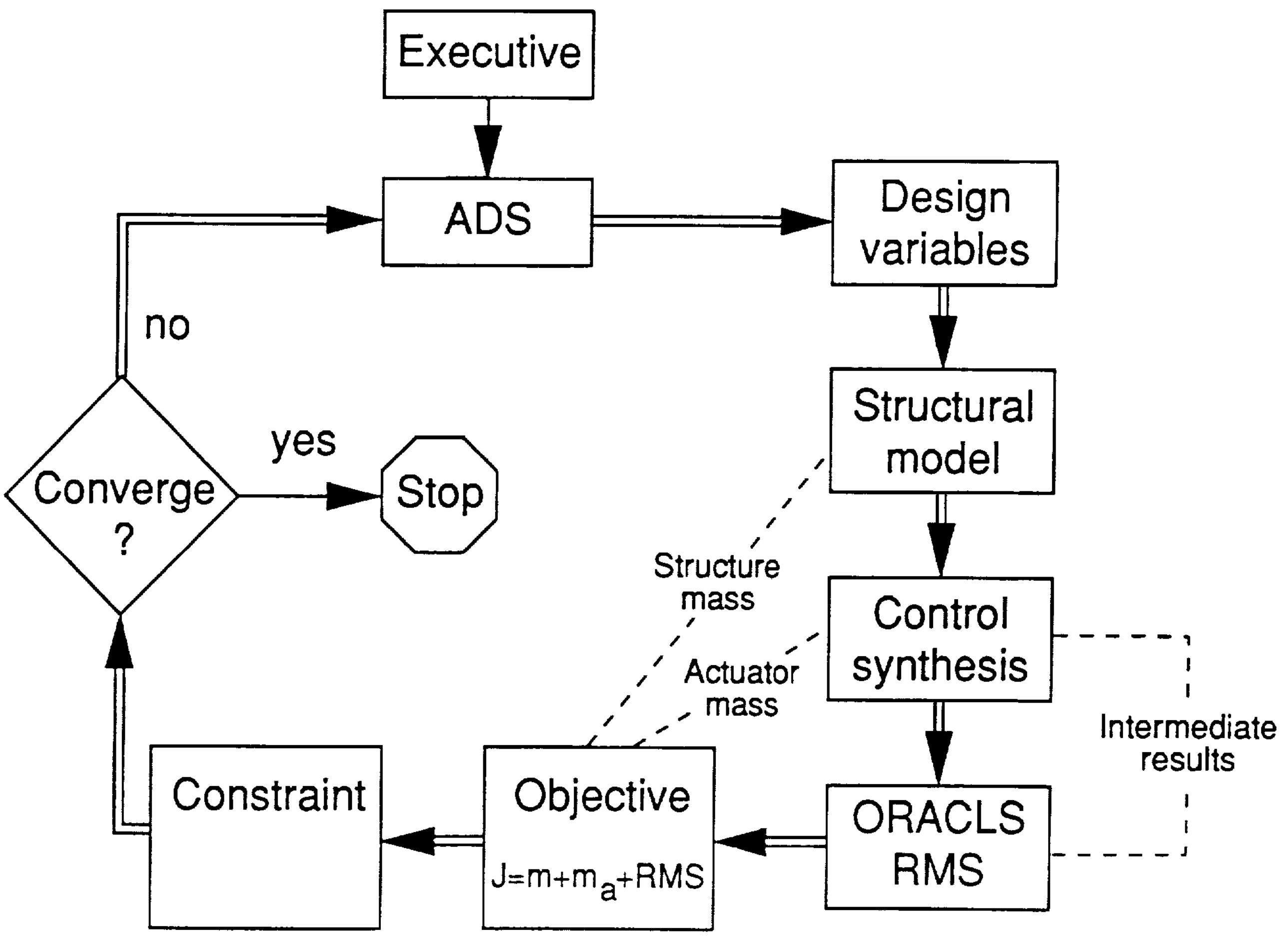
The Earth Pointing Satellite (EPS), shown below, is a derivative of the proposed platforms for study of Earth Observation Sciences (EOS).[14] This class of structure is receiving considerable attention for future missions involving remote sensing of the Earth's environment and resources. The CSI Analytical Design Methods team at the NASA Langley Research Center is planning studies of the EPS to test various methodologies for integrated controls and structures design.

To address the problem formulation mentioned on the previous page, an objective function has been examined which includes structural mass, controller mass and a pointing performance measure. It is believed that this objective, with proper weighting of the objective parts, will yield a great deal of insight into the controls and structures trade-off. The next chart shows the ease with which CS^3 can be modified to handle this problem formulation.



CS^3 Flowchart for the EPS Design Problem

Evaluating the objective function for the EPS design problem requires structural and control analyses plus calculation of a stochastic measure of the rms pointing error. Because CS^3 can share data easily, the computation of the objective is quite straightforward. The structural mass is obtained from the finite element model. Actuator mass is a function of the control gains, hence, the control law synthesis must be performed first. Subsequently, the rms pointing error, which uses numerous intermediate calculations performed in the control law synthesis, is carried out. Thus, CS^3 can be readily changed to study different formulations of the integrated design. Conventional design approaches, which use data base systems, would require either new information to be written to the data base or 'cold' starts of program modules when the problem formulation drastically changes.



Future Modifications to CS^3

A number of enhancements are envisioned to CS^3. These include plotting capabilities, new elements in the finite element library, additional control synthesis techniques and better user interfaces. In addition, new algorithms for vectorization and perhaps parallelization will be included. The code will remain a tool for studying CSI and designing linear time-invariant controlled structures. The main purpose of the architecture is to alleviate the computational burden from the researcher to enhance the study of design methodology.

There are other classes of problems which involve time-variant and/or nonlinear systems. At the present time, CS^3 cannot address these problems. However, the architecture proposed herein should be exploited for these classes of problems when possible.

It is recognized that this architecture does not lend itself well to big problems on small computers. Hence, there needs to be continued development of data-base type design codes. Hopefully, future data-base type software will more closely couple the control and structure disciplines and thereby promote as much interdisciplinary research as possible.

- Pre & post processing
  - User interfaces
  - Graphics
- Additional capabilities
  - More structural elements
  - More control synthesis methods
- Faster algorithms
  - Vectorization

Concluding Remarks

A computational architecture has been implemented for preliminary controlled structure design which greatly enhances the researchers freedom in formulating integrated design problems. By incorporating codes from separate disciplines within a single executable program, optimization of the control-structure coupled-field problem can be solved as easily as a single-field optimization problem. A prototype code called CS^3 has been described which demonstrates the flexibility of the architecture. Example problems show the architecture to be amenable to design methodology studies.

It is the authors' hope that by eliminating some of the computational burden associated with CSI, the proposed architecture will permit increased research into the underlying physics of CSI.

- The proposed in-core architecture greatly reduces user data management.
- By incorporating structures, controls and optimization into one program, interdisciplinary design is encouraged.
- A prototype code called CS^3 which uses the in-core architecture, has been successfully applied to CSI design problems.

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